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## Scaling of divertor heat flux profile widths in DIII-D

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### Abstract

New scalings of the dependence of divertor heat flux peak and profile width, important parameters for the design of future large tokamaks, have been obtained from recent DIII-D experiments. We find the peak heat flux depends linearly on input power, decreases linearly with increasing density, and increases linearly with plasma current. The profile width has a weak dependence on input power, is independent of density up to the onset of detachment, and is inversely proportional to the plasma current. We compare these results with previously published scalings, and present mathematical expressions incorporating these results.

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## I. Introduction

The width of the divertor heat flux profile  $w_{q,div}$  is of great interest in future large tokamaks as well as many present devices. Previous studies examining the parametric dependence of  $w_{q,div}$  have arrived at diverse scalings [1] in JET [2], ASDEX-Upgrade [3], JT60-U [4,5], DIII-D [6,7], and NSTX [8] with results somewhat at variance with each other. We attempt here to perform a new series of experiments in DIII-D to obtain scaling of the divertor heat flux peak value, profile width, and divertor plate power as a function of plasma input parameters, with the maximum number of divertor and scrape-off layer (SOL) diagnostics brought to bear.

We performed measurements in lower single-null edge localized mode (ELM) H-mode diverted configurations that, due to the strike-point positions, were not strongly pumped. We varied the plasma current  $I_p$  at constant toroidal field  $B_T$ , and varied line-averaged density  $\bar{n}_e$  at constant  $I_p$  and  $B_T$ . The neutral beam injected power  $P_{inj}$  was varied at constant  $I_p$  and  $B_T$ ,  $B_T$  at constant  $I_p$ , and  $B_T/I_p$  at constant  $q_{95}$ . The divertor heat flux was calculated from infrared camera measurements using a new high-resolution fast-framing IR camera.

The IR camera recorded divertor plate surface thermal emission at multi-kilohertz frame rates through the whole discharge to allow measuring time-averaged data as well as rapid changes due to ELMs. The heat flux at each position in the radial profile was calculated at each of the times steps using the THEODOR 2D heat flux analysis code [9]. We show scaling of the divertor peak heat flux and profile width as a function of the parameters varied, and compare with published results from other devices.

## II. Peak divertor heat flux

For each discharge, one or more time intervals of interest were selected where plasma conditions varied little during the interval. The average of each quantity was compiled for each interval. Low-frequency ELMs are included in the average.

Figure 1 shows the peak heat flux  $q_{div,peak}$  at the inner (ISP) and outer strike points (OSP) plotted against the input power  $P_{in}$  (neutral beam heating plus Ohmic heating power), where  $I_p = 1.3$  MA,  $B_T = -1.9$  T were held constant. Density was between  $5.2$  and  $6.5 \times 10^{19} \text{ m}^{-3}$ , except at the highest power, where  $\bar{n}_e = 2.3 \times 10^{19} \text{ m}^{-3}$ . Linear fits are shown. A linear dependence of  $q_{div,peak}$  on input power can reasonably be concluded, with the caveat that not all points were taken at the same density. Without the highest power point, we still see a linear dependence.

Figure 2 again shows  $q_{div,peak}$  at the ISP and OSP, this time plotted against line-averaged density, where  $P_{in} = 4.9\text{-}5.1$  MW except for the densities  $\bar{n}_e = 5.2 \times 10^{19} \text{ m}^{-3}$ , where  $P_{in} = 7.2$  MW, and  $\bar{n}_e = 6.8 \times 10^{19} \text{ m}^{-3}$  where  $P_{in} = 4.1$  MW. Toroidal field was held constant at  $B_T = -1.9$  T, and plasma current was held at  $I_p = 1.3$  MA. Linear fits to the data are shown. If the two density values where  $P_{in}$  varied are eliminated, the dependence of  $q_{div,peak}$  on density still is linear.

Figure 3 depicts the  $q_{div,peak}$ , now plotted against plasma current, showing a linear dependence. Toroidal field was held at  $B_T = -1.9$  T, and  $P_{inj} = 4.7\text{-}5.0$  MW except for the point at  $I_p = 1.3$  MA where  $P_{inj} = 4.1$  MW. Density was not held constant, but allowed to vary at the natural H-mode density, because of practical difficulty measuring the heat flux at the OSP during the plasma pumping that would have been required to maintain constant density. Figure 4 shows the line-averaged density variation during the  $I_p$  scan. Because of the density variation in this set, this plot does not prove the variation with  $I_p$  alone. In

combination with the density scan at constant  $I_p$ , the dependence on  $I_p$  will be extracted from a multi-parameter fit to a larger data set in a later analysis.

Figure 5 shows  $q_{div,peak}$  plotted against  $B_T$  at nearly constant safety factor  $q_{95} = 3.6-3.7$ , with linear fits. Density ranged from  $\bar{n}_e = 3.2 \times 10^{19} \text{ m}^{-3}$  at the lowest field to  $\bar{n}_e = 5.8 \times 10^{19} \text{ m}^{-3}$  at the highest field. There are not enough data points to conclusively show a linear dependence, but that would be consistent with the data. Since we know from Fig. 2 that the  $q_{div,peak}$  decreases with increasing density, this indicates that if density were held constant,  $q_{div,peak}$  would increase faster than linearly with increasing toroidal field magnitude at constant  $q_{95}$ .

The work of Makowski [10] indicates that the heat flux profile width does not depend specifically on the toroidal field. If the width does not change the peak cannot change, by conservation of energy. Therefore most likely the dependence of the peak heat flux directly on toroidal field is weak if any. The fits to  $q_{div,peak}$  vs. input power in Fig. 1 nearly pass through the origin, which we expect it should since there will be no steady-state heat flux at zero input power. We will assume here that the correct fit should pass through zero. We also know from previous work [7] that the heat flux depends as expected on flux expansion from the outer midplane to the divertor plate. This means the dominant dependence of  $q_{div,peak}$  at the outer strike point as found above is expressed by

$$q_{div,peak,out} = aP_{in}(9.9 - 9.3n_e)(-1.5 + 3.9I_p)(B_{div}/B_{mp}) \quad , \quad (1)$$

where  $n_e$  is the line-averaged density in units of  $10^{20} \text{ m}^{-3}$ ,  $B_{mp}/B_{div}$  is the ratio of poloidal magnetic fields at the outer midplane separatrix and divertor which gives the flux expansion,  $I_p$  is in megamperes, and  $q_{div,peak,out}$  is in units of  $\text{MW}/\text{m}^2$ . For the inner strike point,

$$q_{div,peak,in} = bP_{in}(3.8 - 3.7n_e)(-0.7 + 1.5I_p)(B_{div}/B_{mp}) \quad . \quad (2)$$

For the discharges used here, the flux expansion at the outer strike point was 6.7 and at the inner strike point, 3.1 (again referenced to the outer midplane separatrix). By plotting  $q_{div,peak,outer}$  vs the [right hand side of (1)]/a and drawing a line through the data and the origin, we find  $a = 0.006 \pm 0.001$  and an analogous procedure for equation (2) gives  $b = 0.05 \pm 0.008$ . Other fitting parameters in equations (1-4) have a comparable fractional margin of error.

### III. Divertor heat flux profile width

Profile widths discussed here are full width at half maximum (FWHM) values for the ISP and OSP respectively. Widths are obtained at each time point and averaged over the time intervals of interest. Here  $w_{q,div}$  shows no dependence on  $P_{in}$  (not shown). This is consistent with  $q_{div,peak}$  varying linearly with  $P_{in}$  in the sense that energy is conserved when  $P_{in}$  changes.

Figure 6 shows the outer and inner  $w_{q,div}$  plotted against density, for the same density scan as above. There is no effect at low density, but there is a threshold density where the profile becomes wider. Radiated power increases at higher density, but not enough to account for the decreased peak heat flux at the measured widths. It is likely that some energy is deposited in locations that are not measured.

In Fig. 7 is seen  $w_{q,div}$  plotted against  $I_p$ , for the current scan already described. We see that widths become larger at low current. The fitted curve for the ISP is linear, but for the OSP, a better fit goes inversely as nearly the first power of the plasma current. No ISP heat flux peak was seen at the lowest  $I_p$ . We expect the current dependence of the inner width would be of a similar functional form to that of the OSP if more data were available. In Fig. 3, the peak heat flux for this case at the ISP is very small. The dependence  $w_{q,div} \propto 1/I_p$  at least

at the OSP from Fig. 7 is consistent with  $q_{div,peak} \propto I_p$  from Fig. 3 so that total power is preserved when  $I_p$  varies.

Because the density scan was performed at constant  $I_p$ , we know the effect of density on the heat flux profile width independent of  $I_p$ . Fig. 6 shows that the effect of density on  $w_{q,div}$  is very weak below the detachment threshold. As shown in Fig. 4, the  $I_p$  scan was performed at densities below this threshold so that density dependence does not enter significantly in the  $I_p$  dependence depicted in Fig. 7.

The plot in Fig. 8 shows  $w_{q,div}$  versus toroidal field at constant  $q_{95}$  for the same discharges as described for the peak heat flux scaling. The widths decrease linearly with the magnitude of the toroidal field. This decrease in  $w_{q,div}$  is consistent with the increase in  $q_{div,peak}$  with increasing magnitude of toroidal field at constant  $q_{95}$ .

Again, we have indications that the width does not depend specifically on the toroidal field [10]. The dependence of the width on power and density are weak (for densities below the detachment threshold). Again taking into account the flux expansion, the dominant  $w_{q,div}$  scaling from Fig. 7 for the outer divertor heat flux can be expressed as

$$w_{q,div,out} = 0.0049(B_{mp}/B_{div})/I_p^{1.06} \quad , \quad (3)$$

where,  $I_p$  is in megamperes, and  $w_{q,div,out}$  is in meters. Over the range of data in Fig. 7, the inner strike point gives

$$w_{q,div,in} = (B_{mp}/B_{div})(0.0077 - 0.0023 I_p) \quad . \quad (4)$$

#### IV. Comparisons with other empirical scalings

Loarte summarized several empirical scalings in Ref. 1, pointing out the areas of disagreement. Here we compare the functional dependences seen above with those scalings.



The linear dependence of  $q_{div,peak}$  on power seen above is in agreement with the JET, ASDEX-Upgrade (DIVIII), and previous DIII-D scaling, but not the ASDEX-U (DIVI) scaling. We note that several of those studies use divertor or target power rather than input power. We find the same linear correlation of peak heat flux with target power as with input power.

We have not observed a clear dependence of peak heat flux on toroidal field at fixed  $I_p$  in the present data, unlike the previous DIII-D study which found a variation of  $1/B_T^{0.5}$ . The linear increase in peak heat flux with  $I_p$  peak agrees with the previous DIII-D result.

The ASDEX-U scaling found  $q_{div,peak}$  varied inversely with density, which we also see.

The  $w_{q,div}$  we use here is different than the  $\lambda_q$  of the referenced studies, which defined an effective width by dividing the strike point power by the peak heat flux. We find in agreement with NSTX, JET IR and ASDEX-Upgrade (DIVII), essentially no (or very weak) dependence of the width on power. We find in agreement with NSTX that the width decreases with increasing plasma current, approximately as  $1/I_p$ .

## V. Conclusion

In the present study we find that peak heat flux varies linearly with input power, inversely as density, linearly with plasma current with a caveat that density was not fixed, and linearly with the magnitude of the toroidal field with  $q_{95}$  held constant.

We find FWHM  $w_{q,div}$  depends not at all on power, and not on density at low density. There is a density threshold for profile broadening associated with the onset of detachment. We see  $w_{q,div}$  varies inversely with the  $I_p$  and decreases linearly with increasing  $B_T$  at constant  $q_{95}$ .

We expect to examine this data set further with other fitting techniques as well as making a study of the ELM heat flux profiles from the parameter scans above.

**Acknowledgment**

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## Figure Captions

Fig. 1: Peak heat flux at the ISP and OSP plotted against the input power. Linear fits to the data are plotted, with fitting parameters shown in the boxes. The dependence on input power appears to be linear.

Fig. 2: Peak heat flux at the ISP and OSP plotted against line-averaged density. As density increases,  $q_{div,peak}$  decreases linearly.

Fig. 3: Peak heat fluxes, now plotted vs  $I_p$ . As  $I_p$  increases,  $q_{div,peak}$  increases linearly.

Fig. 4: Line-averaged density variation during the  $I_p$  scan. All the densities are below the detachment threshold.

Fig. 5: Peak heat fluxes plotted against  $B_T$  at nearly constant safety factor, showing a reasonable fits to a line.

Fig. 6: OSP and ISP heat flux profile widths plotted against density. Density variations below the detachment threshold have no effect on the width.

Fig. 7: Profile widths plotted against plasma current. The OSP shows a clear inverse dependence of width on  $I_p$ . The inner strike point dependence is less clear, in part because the heat flux is very small at low plasma current.

Fig. 8: Profile widths versus toroidal field at constant  $q_{95}$ . The trend is described by linear fits.

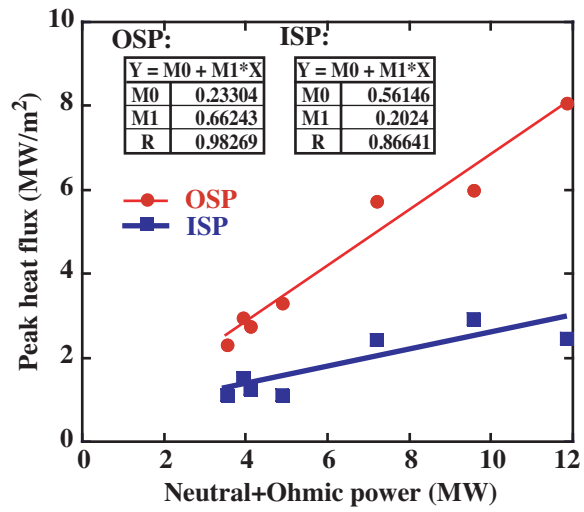


Figure 1

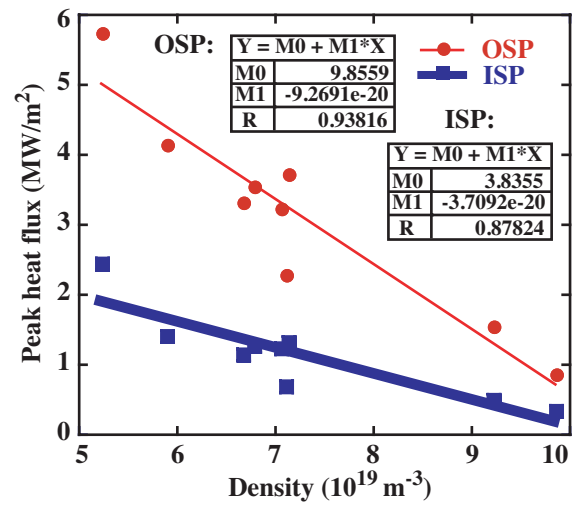


Figure 2

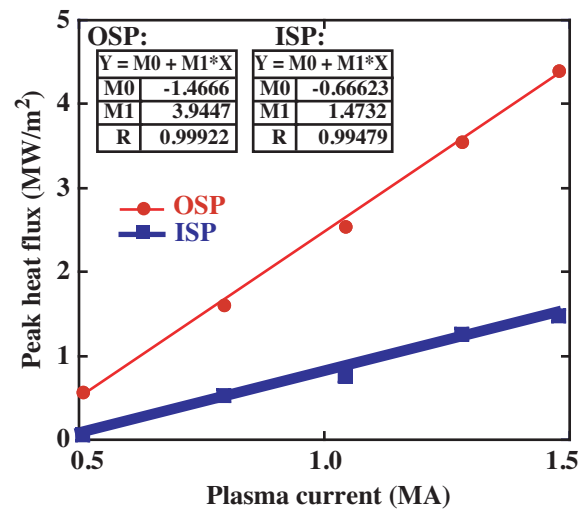


Figure 3

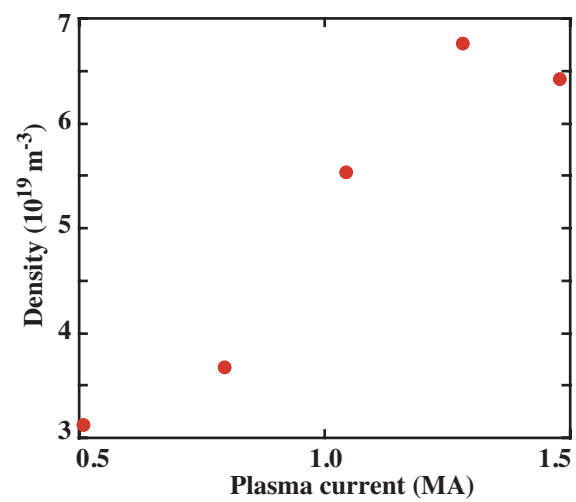


Figure 4



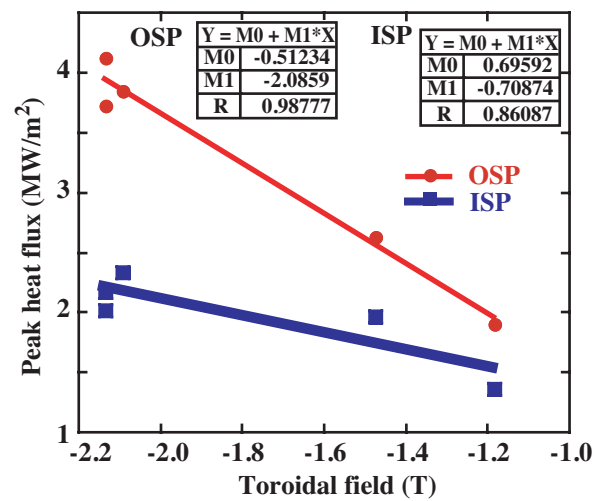


Figure 5

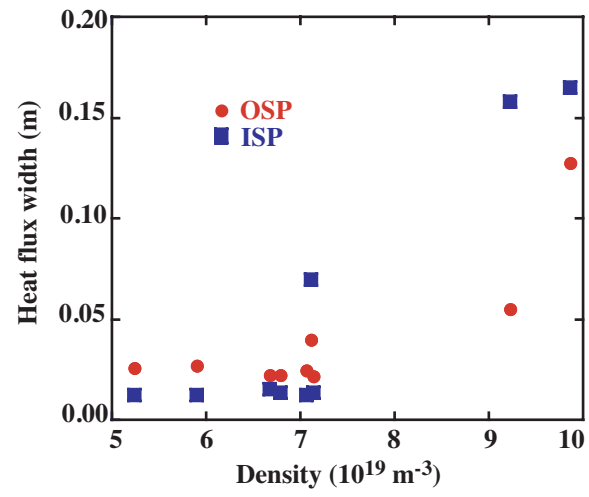


Figure 6

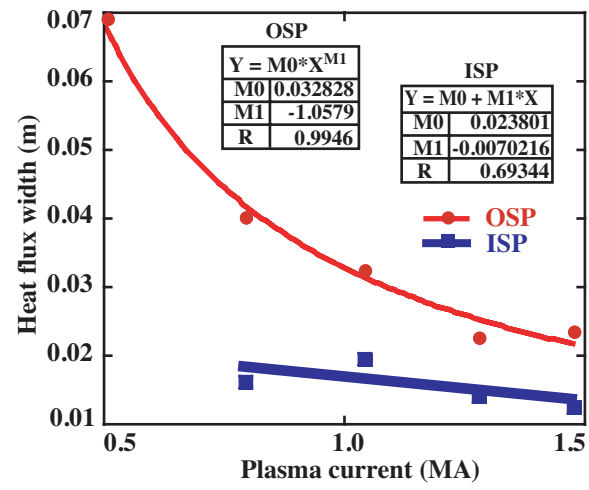


Figure 7

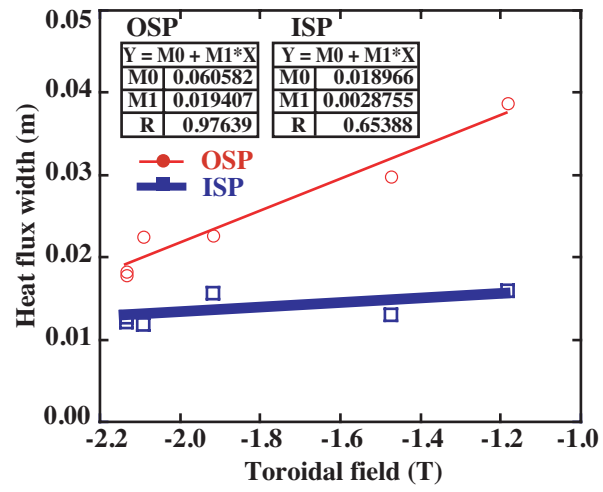


Figure 8